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INFORMATION ON SOVIET WORK ON CORROSION FATIGUE OF METALS

Introduction

This report represents a compilation from available Soviet literature on research in the field of corrosion fatigue and is presented in the form of representative excerpts from the published literature.

While the volume of published research was deemed adequate for the compilation of a comprehensive survey, it should be noted that the number of individual contributors (to the open literature) is somewhat restricted, G. V. Akimov, G. V. Karpenko, A. V. Ryabchenkov, and S. G. Vedenkin being the chief authors.

The number of scientific institutions at which the research was conducted is likewise limited. Establishments identified with this work are the Central Scientific-Research Institute of Technology and Machine Building and the Moscow Institute of Steel.

The organization of the subject matter covered in this report follows contemporary Soviet practice. The report is divided into the following six chapters: I. Factors Affecting Corrosion-Fatigue Resistance of Steel; II. Effect of Electrochemical Factors on Corrosion-Fatigue Resistance of Steel in Electrolytic Solutions; III. Increasing Corrosion-Fatigue Resistance Through Surface Hardening; IV. Electrochemical Methods of Increasing Corrosion-Fatigue Resistance of Steel; V. Effect of Protective Coatings on Fatigue and Corrosion-Fatigue Resistance of Steel; and VI. Anticorrosive Nitriding of Structural Steel as a Method of Increasing Fatigue and Corrosion Fatigue Resistance.

Numbers in parentheses in the report refer to the appended sources.

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Recent Publication

The book Korroziionno-Mekhanicheskaya Prochnost' Metallov, Mashiz, Moscow, 1955 by L. A. Glikman, was received while this report was in its final stages of organization and too late for its inclusion therein. The table of contents of Glikman's book is as follows:

- I. Effect of Simultaneous Corrosion and Static Pressure on Strength (Corrosion Cracking)
 1. Some Experimental Data on Corrosion Cracking
 2. Effect of Stress on Corrosion Cracking
 3. Various Means and Methods of Preventing Corrosion Cracking
- II. Fatigue Resistance of Metal When Subject to Corrosion (Corrosion Fatigue)
 1. Experimental Data on Corrosion Fatigue in Fresh and Salt Water
 2. The Effect of Various Factors on Corrosion Fatigue (Total Cycles, Cyclic Frequency, Media, Stress and Type of Cycle, Magnitude)
 3. Various Methods of Preventing Decrease of Fatigue Strength Under Corrosion
- III. On the Nature of Corrosion Cracking and Corrosion Fatigue
- IV. Resistance to Cavitational Destruction

Basic Concept

Fatigue failure is the progression of a fine crack through a material as a result of a large number of cycles of stress reversal, usually originating in a surface notch or other stress raiser. High stresses existing at the bottom of the crack make further attack by a corroding medium more severe than the corrosion might be under ordinary unstressed conditions. Therefore, the presence of a corroding medium which may initiate notches in the form of corrosion pits, and the presence of alternating or cyclic stresses which tend to produce fine cracks, go hand in hand to produce early failure of parts subjected to such conditions.

The fatigue strength of materials is greatly decreased by the presence of a corroding medium. The general phenomenon is referred to as corrosion fatigue and usually is of a transcrystalline nature.

The existence of alternating stresses may tend to cause considerable damage to any protective film built up in the normal course of the action of a corrosive medium. Continual damage to this film may be a source of the further development of cracks which accelerate fatigue failure.

1. FACTORS AFFECTING CORROSION-FATIGUE RESISTANCE OF STEEL

Steel Composition and Heat Treatment

The practical observations and experimental results of many Soviet investigators indicate that the chemical composition of carbon steels has little effect on their corrosion fatigue resistance in electrolytic solutions.(2)

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The static strength of carbon steels, particularly the tensile strength, varies widely, depending upon the carbon content; however, the corrosion fatigue of carbon steels in fresh water, which is determined by the corrosion resistance, is practically the same regardless of carbon content and lies in the range 12-15 kg/sq mm.(1)

A. V. Ryabchenkov, one of the most prolific of Soviet writers on stress corrosion, reports that the corrosion resistance of low-alloy steel in fresh water is almost the same as that of carbon steels. According to this scientist a characteristic peculiarity of low-alloy steels is their sharp decrease in fatigue strength in corrosive media. Thus, the corrosion resistance of chromium-vanadium steel in fresh water is approximately one fourth as much as in air. Similarly, silicon-nickel steel, which has the highest tensile and fatigue strength in air, becomes one of the poorest of steels in water (fatigue strength 77 kg/sq mm in air, 12 kg/sq mm in water). The corrosion fatigue resistance of copper steel in salt water is no better than that of carbon steels. Nickel steel, however, has a definite (twofold) superiority over carbon and copper steels in resistance to corrosion in salt water. Chromium-nickel steel also has a noticeably greater corrosion resistance in salt water than carbon steels.(2)

In their study on the effect of atmospheric corrosion on the fatigue strength of structural steels, Ryabchenkov and Ye. L. Kazimirovskaya found that the humidity and the sulfur dioxide content of the air have a substantial effect on fatigue strength. However, the corrosion fatigue resistance of steel may be considerably increased by surface hardening (shot blasting, high-frequency induction hardening, or nitriding).(29)

According to S. G. Vedenkin, low-alloy chromium-nickel-copper steel NL-2 (0.80% Cr, 0.40% Ni, 0.3% Cu, 0.18% C), smelted from the naturally alloyed cast iron made from Orsk-Khalilovsk ore, had a corrosion resistance of 10 kg/sq mm in a 3% solution of sodium chloride at a 10^7 cyclic stress while, under similar conditions, the St 3 See PDD Summary 148 for the chemical composition.) steel had a resistance of only 6 kg/sq mm. The fact that some low-alloy steels and carbon steels have practically the same corrosion-fatigue resistance coincides fully with the corrosive characteristics of these steels when unstressed in neutral solutions.(3)

The experience of many Soviet authors indicates no great difference between the corrosion resistance of commercial steels (i.e., carbon and low-alloy steels) in neutral media.

Soviet research has shown that the corrosion process of carbon and low-alloy steels in neutral solutions is not at all dependent upon their structure or composition.

Moreover, low-, medium-, and high-alloy steels as well as many low-alloy structural steels differ little in their corrosion-fatigue resistance or in their static corrosion resistance.

Researchers have concluded that strength and fatigue strength in air do not serve as criteria for the behavior of steels under conditions of corrosion fatigue and that, where these conditions exist, it may be useless to substitute one steel for another. However, this does not apply to stainless, acid-resistant alloys. If the content of alloying elements (principally chromium) in steel is increased to the point where the steel becomes stainless, its corrosion-fatigue resistance becomes considerably improved.

Steel structure, which is determined by heat treatment, has a substantial effect not only on static strength but on fatigue strength as well.

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Ryabchenkov cites a non-Soviet source (Gough, H., *Journal of the Institute of Metals*, No 2, 1932, p 17) to indicate that under conditions of corrosion fatigue, hardened and tempered steel is not superior to annealed steel and that some annealed low-alloy steels have greater corrosion-fatigue resistance than hardened and tempered steels. Ryabchenkov tested the corrosion fatigue resistance of grade 45 (See FDD Summary 148) steel specimens, some of which were normalized at 840° and others which were hardened at 830°, water quenched, and tempered at 560° for one hour. Tests were conducted on a special TsK-2 machine designed by the Central Scientific-Research Institute of Technology and Machine Building for corrosion-fatigue testing. His tests showed that hardening and tempering results in a greater loss in corrosion-fatigue resistance than does normalization. In absolute corrosion resistance, however, the hardened and tempered steel was 32 percent superior to normalized steel.(2)

Media

Atmospheric corrosion is one of the most common types of corrosion. About 80% of all metal structures are subject to atmospheric corrosion.(4) It is small wonder then that great efforts are being made to increase the life of machines, structures, and other metal products.(5)

Atmospheric corrosion is a form of electrochemical corrosion with the corrosive process occurring under a film of moisture.(2)

This electrochemical corrosive process, occurring as a result of the presence of a thin layer of electrolyte on the surface of the metal, differs somewhat from the electrochemical corrosive process in metal submerged in an electrolytic solution.

The difference is that the thin film of moisture (electrolyte) is a weak obstacle against the diffusion of the oxygen in the air to the surface of the metal. Thus the atmospheric corrosion process occurs primarily with oxygen depolarization even in a relatively acid media.(6)

Atmospheric composition and humidity are regarded as very important factors in atmospheric corrosion. The rate of corrosion as well as the very mechanics of the corrosive process are dependent upon the humidity.(2)

N. D. Tomashov, a well known Soviet corrosion engineer, classifies various types of corrosion on the basis of the moisture content of the corroding surface. He lists three types of atmospheric corrosion: dry, moist, and wet.

Atmospheric corrosion of the latter two types relates to electrochemical corrosion.(4)

When metals are oxidized in the atmosphere, the products of corrosion usually remain on the metal.(2)

In studying the corrosion resistance of carbon and low alloy steels under various atmospheric conditions, Vedenkin found that the average annual loss from corrosion of carbon steel was 135 g/sq m in rural areas and 903 g/sq m in a railroad station.(7)

Because many metal structures subject to atmospheric corrosion are also subject to cyclic stress and because the literature contains no data whatever on fatigue strength under conditions of atmospheric corrosion, this matter is of great and practical interest.

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To evaluate corrosion fatigue resistance under various atmospheric conditions, tests were conducted with normalized grade 45 (See FDD Summary 148) steel specimens. The tests were conducted on Yak-8 type machines developed by the Central Scientific-Research Institute of Technology and Machine Building.

Results indicated that there is a distinct relationship between corrosion-fatigue resistance and atmospheric conditions. An increase of relative humidity from 58 to 100% resulted in a corrosion-resistance decrease of 12%.

Characteristic corrosion-fatigue fractures were observed in specimens subjected to corrosion in an atmosphere saturated with steam and containing some sulfur dioxide. The fractures were intercrystalline in character and typical of corrosion fatigue, since static fracture is characterized by the appearance of groups of fractures.(2)

Cyclic stress corrosion in a 100% humid atmosphere containing sulfur dioxide changes with considerable rapidity from uniform to nonuniform corrosion, with intensive, deep corrosion occurring only in certain relatively small areas. Such conversion of corrosion (from uniform to nonuniform) is quite characteristic under conditions of corrosion fatigue.(8, 9, 10)

The undesirable corrosion conversion occurring during stress corrosion is the direct result of the electrochemical heterogeneity of the surface of the metal damaged by the cyclic stresses while in the electrolytic solution.(2)

An important characteristic of the simultaneous action of corrosive media and alternating stress on metal is that it exceeds the sum total of their destructive effects if separately applied.(6, 11)

The oxide coating formed on the surface of the metal by corrosion, which generally retards or even halts further static corrosion, is destroyed, to some degree, by cyclic stresses and loses its protective properties.(11)

These circumstances create favorable conditions for increased corrosion and, primarily, for the conversion of uniform corrosion to local, pit corrosion.

Corrosion engineering has demonstrated that stress raisers greatly decrease fatigue strength. Consequently, it may be assumed that surface pitting (caused by corrosion) also acts as a stress raiser and thereby magnifies the effect of cyclic stresses. Moreover, with sufficient corrosion fatigue damage the products of corrosion, whose volume considerably exceeds that of the initial material, creates additional stresses in the corrosion fatigue fractures and, in turn, facilitates fracture growth.(2)

It has been shown that the rate of corrosion in many metals is increased as the concentration of neutral salts is increased to a definite limit. The increase in the rate of corrosion is caused by two factors: as the salt concentration is increased the electrical conductivity of the solution is also increased, thus permitting a rise in corrosive current; the increase in the concentration of such anions as Cl greatly decreases the protective properties of the oxide film and, consequently, serves to increase the rate of corrosion.(6)

Vedenkin notes that the rate of corrosion of structural steels in acid solutions with a decreased pH, which do not act as oxidizers, is greatly increased.(3)

As the pH value is increased, the solubility of the ferrous hydroxide is decreased, the protective film becomes more stable, and thus the rate of steel corrosion in the presence of high pH values is decreased. Thus the corrosion fatigue resistance of steel becomes greater.(2)

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Corrosion Retarders

The corrosion-fatigue resistance of parts subject to water corrosion may be considerably increased by the introduction of corrosion retarders into the water. Chromates and bichromates of alkali metals, such as K_2CrO_4 and $K_2Cr_2O_7$, are altogether effective. These compounds are universal passivators since they sharply curtail the rate of corrosion of nearly all metals. Only a small amount of chromate or bichromate (0.5 g/l) is needed to halt the water corrosion of unstressed steel.

A simple laboratory experiment has indicated that a considerably greater quantity of retarder is needed to curtail water corrosion of steel under cyclic stress than when the steel is not under stress.(2)

Testing Equipment

During the past few years the USSR has developed various machines and devices for corrosion-fatigue testing in liquid media. The Moscow Institute of Steel has designed a machine for testing wire specimens under symmetrical flexure of various frequencies. Stress in the specimen is created by simultaneous flexure and torsion.

A. N. Mitinskiy, Ye. S. Reynberg, R. A. Bogranov, and I. V. Kudryavtsev are among the scientists who have developed and designed corrosion-fatigue testing equipment.(30)

Conclusions

The chemical composition of carbon and many low-alloy steels has little practical effect on their corrosion-fatigue resistance in electrolytic solutions. Of the low-alloy steels, nickel and chromium-nickel-copper steel possess the best corrosion resistance in salt water.

Stainless, high-chromium steels possess sufficiently high corrosion-fatigue resistance (21-25 kg/sq mm) in neutral electrolytic solutions. Under the action of salt water, however, their fatigue strength is considerably decreased (up to 30%).

The heat treatment of structural steels (hardening and tempering), which greatly increases fatigue strength in air, has either little effect or no effect at all on corrosion-fatigue resistance in electrolytic solutions.

The chemical composition of the corrosive medium has a very great effect on the corrosion-fatigue resistance of steels. Of the electrolytes, acid solutions cause the greatest decrease of fatigue resistance while alkaline solutions cause the least decrease. Neutral media, and particularly sodium chloride, are midway between the acids and alkalis. As the concentration of sodium chloride in the solution is increased, the corrosion resistance is decreased.

The introduction of materials into water to retard the rate of corrosion substantially increases the corrosion-fatigue resistance of steel.

Although atmospheric corrosion has a lesser effect upon the fatigue strength of steel than electrolytic corrosion, it too is of some significance.

It has been established that the fatigue strength of normalized medium-carbon steel is decreased 12% in a humid atmosphere not containing sulfur dioxide and 19% when sulfur dioxide is present (0.27% SO_2). This indicates that in designing machine parts operating under cyclic stress in a corrosive atmospheric medium, the decrease of fatigue strength caused by corrosion must also be taken into account.

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In determining the fatigue strength of steel parts, fatigue tests must be conducted under corrosive conditions simulating those in which the parts will actually be used.(2) Unless such close simulation is achieved, the tests will prove worthless.

It is also known that fatigue strength decreases as specimen size is increased. When specimens are subjected to alternating stress in a corrosive media, however, corrosion fatigue resistance increases with the size.(30)

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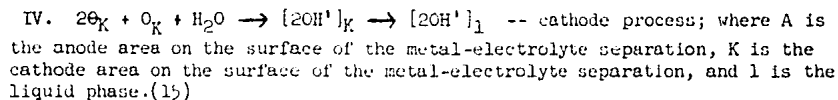
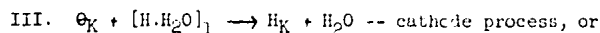
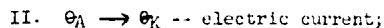
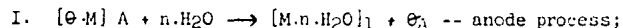
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II. THE EFFECT OF ELECTROCHEMICAL FACTORS ON CORROSION-FATIGUE RESISTANCE OF STEEL IN ELECTROLYTIC SOLUTIONS

Contemporary views regard the corrosion of metal in aqueous solutions of electrolytes as an electrochemical process.(2) G. V. Akimov and A. I. Golubev have demonstrated the conformity between the equilibrium of microelement operation and corrosion, as determined by weight loss.(14) The emergence of corrosive elements in the interaction of metal and medium may have many causes. The principal reasons for the emergence of microcorrosive elements are related, first, to the heterogeneity of the metal phase (resulting from the heterogeneity and structural peculiarities of the metal), to the heterogeneity of the protective films on the surface of the metal, to the heterogeneity of the deformations and internal stresses in the metal, etc; second, to the heterogeneity of the liquid phase; and third, to the variations in external conditions.

Thus, electrochemical heterogeneity is the reason why the surface is separated into cathodic and anodic areas. Moreover, those areas with a more negative electrode potential form the anodes, while areas with a more positive electrode potential form cathodes. On the anode areas, the ion-atoms of the metal may pass into solution and liberate electrons, while the assimilation of the free electrons by the solution occurs on the cathode areas where the metal-electrolyte separation occurs.(2)

According to Akimov, the corrosive process, occurring as a result of the activity of the corrosive elements, may be depicted as follows:



In studying corrosion fatigue from the point of view of the electrochemical theory of corrosion it was first necessary to determine the effect of cyclic stresses on the electroodic potential of metal.

Practical observations have indicated that stress and deformation frequently change the character of corrosion destruction and convert uniform corrosion to corrosion fractures. Depending upon the type of stress, three types of corrosion fractures exist: (1) intercrystalline, (2) intracrystalline, and (3) combined fractures. The first type occurs, as a rule, when metal is subjected to constant tensile stresses in a corrosive media.(2) This type of corrosion is well known and has been exhaustively studied by Vedenkin and V. M. Nikiforova.(16) There are instances, however, when tensile stress corrosion caused intracrystalline cracks (as in magnesium alloys).

When under the simultaneous action of cyclic stresses and a corrosive medium, steel most frequently develops intracrystalline fractures. Ryabchenkov quotes a non-Soviet source, (Whitnam, D. and Evans, U. R., Journal of the Iron and Steel Institute, Vol 165, No 1, p 72) in stating that combined fractures have also been observed, and that corrosion-fatigue destruction has nothing in common with intercrystalline corrosion. (Zihe, F., Berg- und Huettenmaennische Monatshefte, Bd 95, No 2, 1950)

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There are two points of view as to the explanation of selective corrosion in parts subject to corrosion fatigue.(2) According to the first, small pit corrosions appear on the surface of the metal as a result of the corrosion process. Such pit corrosions act as stress raisers with the deepest part of the pit being the area of greatest stress concentration. Thus, the explanation goes, the bottom of the pit will have a more negative potential than the walls of the pit and the surface of the metal and will, consequently, act as an anode. Thus, the pit corrosion will tend to deepen and will gradually cause fracture. This point of view is shared by prominent researchers in the field of corrosion engineering: Akimov (15), Tomashov (17), and Yu. R. Evans. [U. R. Evans, English metallurgist, some of whose works on corrosion have been translated by Akimov and published in the USSR.]

According to the second point of view, corrosion fatigue is comprised of two processes: the first is in that adsorption facilitates the development of microfractures under the influence of cyclic stress, while the second is a purely corrosive process (electrochemical) which occurs within the already formed fractures and thus enlarges them. This point of view is expounded by G. V. Karpenko who believes it to be applicable to corrosive media containing surface-active materials.(18,19)

Moreover, Karpenko also holds that the cycles of alternating stress have a direct effect upon corrosion-fatigue strength. (28)

Thus, according to Karpenko, the existing views on corrosion fatigue which hold that the destruction of metal is a result of microcrystalline corrosion, that is, through an electrochemical process, are wrong. According to these views the grains of the metal are microcells with differing potentials; hence the surface of the metal which is in contact with the electrolyte corrodes. Under the action of cyclic stress, the corrosive process is accelerated and fatigue cracks are formed on the surface of the oxidized grains. Karpenko believes that the investigations of the effect of variable stress on steel specimens do not confirm this theory.

Karpenko notes that the surface layers of test specimens are covered with a large number of transcrystalline cracks and with a lesser number of intercrystalline cracks in which products of oxidation are found. In a nonactive medium, the number of microcracks is considerably less, and depends on the value of the coefficient of cyclic load. For low coefficients which characterize the interval of fatigue destruction, only a single fatigue crack may appear. Karpenko's research further showed a selectivity for "depth corrosion" (i.e., corrosion which passes from the surface to the depth of the metal for a small volume; intercrystalline and transcrystalline corrosion are extreme cases of depth corrosion). The cracks affected by the corrosion lay perpendicular to the acting maximum normal stresses. This corrosion does not have an intercrystalline character, otherwise there would be cracks both in the longitudinal and transverse sections of the test specimen, the cracks making various angles with the surface. For intercrystalline corrosion, torsion would produce cracks making an angle of 45° with the axis of the specimen.

Karpenko concludes that his investigations show that the electrochemical intercrystalline theory of corrosion fatigue cannot explain the selectivity in the formation of fatigue cracks for steel working in a corrosive media.(31)

In yet another article Karpenko discusses two types of corrosion fatigue: (1) the effects of actively corrosive media which continue to attack the material as long as it is exposed and thus continue to lower the endurance limit, and (2) the effects of superficially corrosive media which attack only the surface and thus reduce the endurance limit by a definite amount independent of exposure time. The second type of corrosion is described as an adsorption of weak electrolytes at deformation bands and the opening of numerous microcracks by corrosion.(32)

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Ryabchenkov, in discussing Karpenko's theory, admits that surface-active materials such as oleic acid or saponin actually do decrease the fatigue strength of steel but states that in corrosive media consisting of electrolytic solutions and not containing any surface-active materials, there is every reason to assume that fracture formation through corrosion concentration is related to the effect of cyclic stresses upon the electrode potential of the metal and, consequently, to the development of its electrochemical heterogeneity. Thus the determination of electrochemical characteristics and, particularly, electrode potentials in relation to stress is of great importance in the study of stress corrosion.(2)

Cyclic stresses noticeably lower the electrode potential of steel. As the stress is increased, the rate of displacement of the potential to lower values is also increased. The greatest reduction of electrode potential is brought by changing stresses that produce tension. By using microelectrochemical procedures it has been established that a corrosion element is generated when stresses resulting from loads applied at two neighboring regions of the metal surface differ in magnitude. A study of the two-electrode corrosion element as a function of stress showed that the difference of potential and the current of this element are increased sharply as the stress increases.(13)

Under conditions of corrosion fatigue, some areas of the surface of the metal undergo greater stresses than others. Under the action of these stresses the metallic bond between the ion-atoms of the metal and the electrons may be more easily broken and the protective oxide film may be more easily destroyed. Therefore, the electrode potential of these areas on the surface of the metal must be lower or, under the action of the stress, they could become microscopic anodes.(15)

Little attention has been devoted to the study of the effect of stress on electrode potential, even though the fact that electrode potential does change under stress has been known for many years. (Wiedman, Lehre von Electricitaet, 9, 723, 1893). As a rule, stress and deformation cause a drop in electrode potential. It has been established that increasing stress from zero to a value corresponding to the proportional limit decreases initial potential of iron in a solution ($2\% \text{ NaCl} + 0.1\% \text{ H}_2\text{O}_2$) by 130 mv.(2)

A detailed study by Ye. M. Zuretskiy has shown that residual tensile deformation corresponding to a load of 200 kg/cm^2 , causes a diffusion of aluminum electrode potential in 0.5 moles HCl, copper in 0.5 moles H_2SO_4 , zinc in 0.0125 moles H_2SO_4 , steel in 1.5 moles H_2SO_4 , within 35 mv. Zuretskiy has also established the decrease in time of the difference in potentials between deformed and nondeformed metals.

This researcher made an attempt to calculate the change in electrode potential in the deformation of a magnesium alloy. His theoretical value was several times less than that obtained experimentally. He therefore concludes that the change of electrode potential in the magnesium alloy is related to the destruction of the oxide film during deformation.(12)

Insufficient study has been made of the effect of cyclic stress and corrosion on the electrode potential of steel.(2)

Conclusions

Cyclic stresses considerably decrease the electrode potential of steel. Alternating tensile stresses cause the greatest decrease in electrode potential.

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Microelectrochemical methodology has been used to investigate the distribution of potential on the surface of specimens having stress concentrators. It was found that under conditions of corrosion fatigue the area of stress concentration had a lower potential than its adjoining areas. Consequently there emerges a corrosion (galvanic) element whose electrodes are: anode -- the bottom of the stress raiser, and cathode -- the surface of the specimen adjoining the stress raiser.

Ryabchenkov states that his investigation is the first experimental proof of the electrochemical nature of the corrosion fatigue process in steel when in an electrolytic solution.(2)

III. INCREASING CORROSION-FATIGUE RESISTANCE THROUGH SURFACE HARDENING

The surface of steel generally has a lower fatigue strength than subsurface metal; this is so not only because the surface contains a great number of stress raisers but also because it is the boundary and thus disrupts the crystalline structure of the metal. Moreover, the surface layers also undergo maximum stress from externally applied loads.

Surface hardening by shot-blasting, rolling, or induction hardening are effective means for increasing the fatigue strength as well as the corrosion-fatigue resistance of steel.(2)

Ryabchenkov and V. N. Novikov were the first to show that high frequency induction hardening effectively increases the alternating stress strength of parts subject to corrosion. The fatigue strength of surface-hardened steel shows no decrease in tap water and only a small decrease (25%) in a 3% NaCl solution.(20)

Although surface hardening as a method for increasing corrosion fatigue resistance is a topic of great scientific and practical interest, few investigations have been conducted in this field.

To test the effect of surface hardening upon corrosion fatigue resistance, grade 45 (C 0.44%, Si 0.26%, Mn 0.64%, S 0.029%, P 0.027%) steel specimens were subjected to various tests. The specimens were normalized at 840° C and their surfaces were either polished, shot blasted, rolled, or high-frequency induction hardened. All surface-hardened specimens were annealed at 180° to remove internal stresses. The following corrosive media were used: 3% NaCl solution, 3% NaCl solution saturated with H₂S, 0.5 N NaCl + 0.01 N HCl solution, 0.5 N NaCl + 0.8 N Na₂CO₃ - 0.8 N NaHCO₃ solution.

The results of these tests indicated that cold hardening and especially high-frequency induction hardening effectively increase corrosion-fatigue resistance in nearly all the more common corrosive media.

Tests were also run on the effect of preliminary corrosion on corrosion-fatigue resistance. The tests indicated that corrosion has the greatest destructive effect during the first few days and that it is particularly destructive to nonsurface-hardened steel.

It must be stated, however, that cold hardening and induction hardening increase the corrosion fatigue resistance of steel only in neutral and alkali media, while in acid media they do not increase it but may even decrease it somewhat.(2)

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IV. ELECTROCHEMICAL METHODS OF INCREASING CORROSION-FATIGUE RESISTANCE OF STEEL

There are two methods for the electrochemical protection of metal from corrosion: cathodic protection and electrolytic protection.

The major research in this field was conducted by Soviet scientists. Akimov and Tomashov were the first to formulate the theoretical bases for the electrochemical protection of metals against corrosion. (2)

In a recent work Akimov presented his theory, based on the multielectrode theory, explaining electrochemical protection against corrosion. (21)

After testing grade 45 steel in various media it was concluded that: in tap water (0.004% NaCl) a zinc protector fully prevents corrosion fatigue; in sea water (3% NaCl) cathodic protection considerably increases corrosion fatigue resistance. (2)

V. EFFECT OF PROTECTIVE COATINGS ON FATIGUE AND CORROSION-FATIGUE RESISTANCE OF STEEL

There has been little study devoted to the anticorrosive properties of coatings subjected to cyclic stresses in corrosive media.

Anodic zinc and, to some extent, cadmium coatings assure the electrochemical protection of steel from corrosion and are highly effective in increasing the corrosion-fatigue resistance of steel.

Cathodic coatings (electroplated chromium, nickel, and copper), serve only as mechanical corrosion protectors since they prevent contact between steel and the corrosive media. Such coatings have considerable residual tensile stress and should not be used as the only protection against corrosion fatigue. In fact, these coatings substantially decrease the fatigue strength of steel.

The following requirements are made of coatings used for increasing corrosion fatigue resistance: they should be capable of forming a good bond with the base metal, they should be anodic or completely nonporous if cathodic; they should not decrease fatigue strength in air; they should not be brittle and should not fracture under cyclic stress.

Electrolytic chromium plating of steel causes a considerable reduction in fatigue strength. The fatigue strength of chromium-plated specimens decreases as the plating thickness is increased. Electrolytic chromium plating of carbon steel increases corrosion resistance (by 9%) in tap water while decreasing it (by 13%) in a 5% NaCl solution. Tempering chromium plated parts at temperatures up to 300° does not eliminate the harmful effect of chromium plating upon fatigue strength. However, tempering at 600-650° practically completely eliminates the negative effect of chromium plating upon fatigue strength. The decrease of fatigue strength resulting from chromium plating is due to the great tensile stresses in the chromium plate. The degree of residual stress in the chromium is determined by the technological factors in the electrolytic plating process: current density, electrolyte temperature, and surface preparation prior to plating. Residual stresses increase as current density is increased.

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Electrolytic nickel plating of steel causes a considerable reduction in fatigue strength. Because of this, as well as the cathodic character of the nickel plate, nickel is not recommended as a protective coating against corrosion fatigue. The decrease in fatigue strength caused by nickel plating is, as is in chromium plating, due to the tensile stresses in the plate. The degree of residual stress in the nickel plate is determined by the surface preparation of the base metal and the technological factors of the electrolytic plating process. It is believed that if steel parts are surface hardened prior to plating, fatigue strength will be greatly increased.

The electrolytic plating of steel with zinc does not reduce fatigue strength in air. In sodium chloride solutions zinc plating acts as an effective protector against corrosion-fatigue destruction. The corrosion resistance of zinc plated steel is increased 25% if the steel is hardened and tempered. Zinc plating is recommended for steel parts subject to cyclic stresses and operating in the atmosphere, fresh water, or salt water. (2)

Conclusions

Cathodic chromium, nickel, and copper coatings decrease the fatigue strength of steel. With commonly used plate thicknesses, chromium and nickel reduce fatigue strength 22-35%, while copper reduces strength by 13%.

The corrosion fatigue resistance of electrolytically chromium or nickel plated steel parts may be increased by: more effective electroplating processes (which would assure minimum stress in the plate), high temperature tempering of chromium plated parts, and surface hardening the base metal, thus imparting to it residual compressive stresses.

The electrolytic plating of steel with cadmium provides no electrochemical protection against corrosion in tap water but does increase the corrosion-fatigue resistance of steel in salt water although not as much as does zinc. (2)

VI. ANTICORROSIVE NITRIDING OF STRUCTURAL STEEL AS A METHOD OF INCREASING FATIGUE AND CORROSION-FATIGUE RESISTANCE

There are two types of nitriding. One is for purposes of hardening, the other, for corrosion protection. The latter is distinguished by its shorter exposure to ammonia gas and the higher temperatures at which it is exposed. Anticorrosive nitriding may be used on any nonalloyed steel or cast iron. (2)

The anticorrosive nitriding process was first developed by V. I. Prosvirin, V. D. Yakhnina and Ryabchenkov and was since introduced into Soviet industry. (22, 23, 24) A. N. Minkevich, I. Ye. Kontorovich, A. A. Sovolova, and Yu. M. Lakhtin conducted important research in this field and were the first to introduce this new process into Soviet production. (25, 26, 27)

Laboratory tests indicate that short term anticorrosive nitriding considerably increases the fatigue strength of tool steels. Anticorrosive nitriding also increases fatigue strength of carbon steels by 50-60% and that of chromium steels by 14-27%.

The nitriding process is especially effective in increasing the corrosion-fatigue resistance of carbon steels. Nitrided carbon steel has the same resistance to stress corrosion in tap water as it does in air. The anticorrosive nitriding process increases corrosion resistance of carbon steel 120% in tap water, 95% in a 3% solution of NaCl, and 45% in a water-vapor-saturated atmosphere with a 0.27% content of SO₂.

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The sensitivity of nitrided surfaces to hairlines is decreased considerably, especially in chromium steels.

The principal reasons for the beneficial effect of nitriding on the corrosion-fatigue resistance of steel are: the high anticorrosive properties of the nitrided film which completely protects steel from corrosion in water, industrial atmospheres, and other media; and the presence of considerable residual compressive stress in the nitrided film which substantially increases corrosion fatigue resistance. (2)

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